L $= -58.1 - 1.1 = -59.2$ which is in reasonable agreement with the previous result.

<u>Double Reflector Passive Repeater Loss</u>

Sometimes it is necessary to use two passive reflectors in a back to back configuration to make sharp bends not possible with a single reflector (eg, sending a signal over a hill). These two reflectors will usually be so large and so close that they will be in the near field of each other. It is possible to perform the calculations for the three paths and calculate the loss using the correction factor from Figure 10. A faster way is to calculate the loss using a single passive (using the smaller of the two rectangular reflectors) and adding a correction factor from Figure 13.

Let's consider the previous example of a single 10 foot square passive reflector at the midpoint of a 30 mile path. As we noted previously, the combined path loss for this case is

L $= -94.2$ dB

Now let's replace the single 10 foot passive by a pair of 10 foot square passives separated by 500 feet.

$Db/Da = 10/10 = 1$

$10 \log(d/[2Da^2/\lambda]) = 10 \log(500/[2 \times 10^2/0.158]) = -4.0$

per the previous calculations. Therefore, the combined loss taking the N factor from Figure 13 is

L $= -94.2 + N = -94.2 - 2.6 = -96.8$dB

RECEIVED SIGNAL VARIATION (FADING)

The predicted values of received radio signal strength are usually based on a standard atmosphere (one which has no ducts, no refractive index discontinuities, and no turbulence). Natural variations from the standard atmosphere that occur at various times and places are produced chiefly by variations in the temperature and water vapor content of the actual atmosphere. They can cause considerable variation (fading) in the actual signal strength received compared to that predicted from a theory which assumes a static standard atmosphere. These variations in the predicted values of signal strength produced by natural phenomena should be considered in the design of a radio communication system.

Predicting fades is not an exact science. Thrower [31] observed,

> "On the philosophical side of the dB ledger, one doesn't like to see a fade but, being practical, you can't make absolute predictions as to whether a path will fade or not, since we live in a terrestrial environment, rather than in theoretical free space. Even path testing is not an absolute way of establishing the reliability of a path, since to do it properly, one would have to run a propagation test over the path, with the planned tower height and with the planned antenna sizes for a minimum of a year in order to obtain data under all environmental conditions, and even that will vary from year to year, witness the drought stricken areas of the country for 1976 - 1977. Tests made, for example, in the Pacific Northwest during last winter, would result in totally different results compared to normal wet years in that region and a planned 11-GHz radio path would be defective when weather conditions return to their more normal saturated state.
>
> It is for these reasons that one cannot, and should not, guarantee a path and the potential system user should be wary of those who offer to guarantee the path because it just can't be done. The experienced systems manufacturer and the experienced consultant don't and won't and shouldn't. The user should always be cautioned that there is always the possibility of fading although the path will be designed using the techniques that have been found to offer best protection against fading."

Most fading can be categorized as atmospheric absorption (including rain attenuation), multipath, diffraction (shadow), loss (earth bulge), antenna decoupling, and ducting. Often, fading is a combination of these types. A general introduction is given in the following paragraphs.

ATMOSPHERIC ABSORPTION

Path loss caused by atmospheric absorption is primarily due to atmospheric gases and rain. At frequencies below 60 GHz, attenuation due to frozen moisture (eg, snow or ice crystals) can be neglected. The only significant loss due to precipitation is caused by liquid raindrops. This loss will be overviewed later. Atmospheric gas absorption is due to resonance of various molecules and a broad nonresonant loss due to oxygen and water vapor. Below 100 GHz, the only significant resonances [3] are due to water vapor (H_20) at 22 and 68 GHz, ozone (0^3) at 67 and

96 GHz, and a broad band of oxygen (O^2) resonances from 61 to 68 GHz. Due to atmospheric pressure, the absorption resonances are broadened so that significant absorption is observed near the resonance frequencies. Oxygen attenuation is sensitive to temperature variations but its contribution is masked by water vapor loss. Water vapor loss is a moderate function of temperature above roughly 26 GHz. With little loss of accuracy, the loss dependency on temperature can be ignored. The above losses have been plotted in Fig. 15. As point of reference, in fog a visibility distance of 10 meters equates to about 10 gm/m^3 of water. Likewise, 50 meters indicates 1 gm/m^3, 100 meters indicates 0.4 gm/m^3, and 500 meters indicates 0.04 m/m^3.

RAIN LOSS

At higher radio frequencies, large amounts of rain can have a significant effect on system radio interference , cross-polarization discrimination , and path attenuation. The interference and cross-polarization discrimination effects are short lived and generally are not a significant degradation to terrestrial paths. Path attenuation, however, has a significant impact on path design. Tillotson [32] observed the considerable effect rain can have on path design. He observed that for a rain rate of 100 mm (4 in)/hr, a normal 4- or 6-GHz path of 30 to 60 km (20 to 30 mi) designed for a 40-dB fade margin would be unaffected by rain. However, to maintain the path within the 40-dB fade range, the path length would have to be reduced to 9.2 km (5.7 mi) at 11 GHz, 3.7 km (2.3 mi) at 18 GHz, or 2.1 km (1.3 mi) at 30 GHz.

The rain attenuation observed on a radio path is a function of the following three variables:

α(dB) $= \beta \gamma L$

β(dB/km) = attenuation of a signal in rain of constant density and rate (attenuation due to point rain rate)

γ = path correction factor (conversion factor from point rain rate to path averaged rate)

L = path length

The attenuation of a signal due to rain is a function of the size distribution of raindrops as well as a function of rain rate and the terminal velocity of the drops. The size distribution is a function of the type of rain (eg, thunderstorm, drizzle), and terminal velocity is a function of raindrop shape which is a function of rain type and wind. Olsen, Rogers, and Hodge [27] suggest that the Laws and Parsons [18] size distribution and the Gunn and Kinzer [14] terminal velocity results are the most reliable data to date. If the raindrops are assumed to be spherical, β is given by Olsen, Rogers, and Hodge [27] as

β(dB/km) $= aR^b$

R(mm/hr) = rain rate

where a and b must be calculated. Based on an assumed spherical shape for raindrops and various rain distributions and rates, Olsen, Rogers, and Hodge [27] calculated the theoretical values for a and b for various atmospheric temperatures. Rain attenuation is a moderate function of temperature. Comparing attenuation of 0° and 20°C, attenuation is slightly greater at 0° for frequencies below 10 GHz or greater than 20 GHz. Table 7 lists values for a and b for 20°C and spherical rain with the Laws and Parsons distribution. These results are in excellent agreement with Medhurst's results [25] for rain rates of 5 mm/hr or greater. Photographs have shown that rain, rather than being spherical, is actually flattened or concave. A slightly better approximation is to assume that raindrops are elliptical. Based on this approximation, vertically polarized signals experience less attenuation than do horizontally polarized signals. Horizontally polarized signals experience attenuation slightly greater than the attenuation predicted by spherical raindrops [25]. Based on Lin's data [19] [21] for 11, 18.1, and 30 GHz and Nowland, Olsen, and Shkarofsky [26] for 13 and 19.3 GHz, Table 8 was produced. The table lists the percentage that vertical attenuation β_v(dB/km) is less than horizontal attenuation β_h (dB/km). The table lists the values of $(100\,[\beta_h - \beta_v]\,/\,\beta_h)$ as a function of rain rate. Rain rate data is taken by measuring the total rain accumulated in a rain gauge in a period of time (integration period) and dividing by the integration time. The measured rain rate varies considerably with rain gauge integration time. A very short integration time produces widely varying results due to wind and spatial variations. A long integration time reduces the effect of short duration high rain rate. Fig.16, based on Lin's results [20] [23], shows the effect of gauge integration time. Bussev [5] observed that a rain rate of 1 mm/hr represented light rain, 4 mm/hr moderate rain, 16 mm/hr heavy rain, and 100 mm/hr represented a cloudburst.

The attenuation measured at one point of a radio path is not totally representative of the attenuation of the path taken as a whole. The relationship between point rain rate attenuation is a complex function of rain gauge integration time and probability of rain cell size and occurrence. Lin [21] [23] suggests that if the point rain rate R is measured with 5-minute integration time, γ is given by

$$\gamma = L' / [L' + L]$$

$L(km)$ = path length

$$L' = 2636 / [R - 6.2]$$

$$R(mm/hr) \leq 10$$

Crane [7] suggests a slightly more complicated model. Lin's model yields a γ factor less than unity. His model is accurate primarily for high rain rates (R greater than 25 mm/hr). Crane's model yields a γ factor less than unity for high rates and greater than unity for low rain rates. This accounts for the observation that although the rain rate at one location may be low, it may be much higher elsewhere. High rain rates, however, indicate that the observation point is near the center of maximum rain intensity. Either Lin's or Crane's result is reasonable for the high rain rates that dominate short high frequency path design. Lin's requires the use of a 5-minute rain rate; Crane's uses a 1-minute rate. Lin, Bergman, and Pursley's results in Fig.16 can be used to convert between rain rates.

The previous calculations have assumed a point rain rate R which will not be exceeded more than a percent of the time. The actual rain rate at any instant is quite erratic. Long-term rain rate data gathered from a single rain gauge requires a very long time base (several years) to yield stable statistics. If the time base is not sufficiently long, the short-term results tend to underestimate (or occasionally overestimate) the long term, large sample average. Data taken over a period of less than 10 years [7] is generally unreliable for moderate rain rates. Incidence of high rain rates at a single point is so low that a much longer time base (a few decades) is required to obtain stable statistics [12]. Fig. 17, based on Lin's 20 years of United States data [23], shows the range of rain rates for various cities. Crane [7] gives estimated rain rates for various locations of the world.

The preceding rain rate data is based on distributions measured over one or two decades. The rain rates obtained from this data represent the rates that would have been measured if the radio path had been operating over the previous long time period. Exactly the same data will probably not be obtained if measurements are made over the next couple of decades. However, this data represents the best estimate of the rain rate which would not be exceeded over any 1 year. The actual rain rate measured over any one specific year will be different than the average value. Average values should not be confused with worst-case values. Osborne [28] observed that the worst-case 1-year rain rates can exceed long-term averages by 2.5 to 10 times. Worst-case month or hour rates can exceed long-term averages by extremely large factors. Engineering paths based on worst-case statistics lead to very uneconomical radio systems. As Osborne [28] observed, at the present time there is no definitive proven solution to this problem. There is no practical method to limit the worst-case outage time for radio paths with loss dominated by rain attenuation.

It should be noted that it is the rainfall rate that determines outage time, not the total annual amount of water that falls. The northwest coast of the United States is a primary example of a very wet region where there are virtually no rain-related path outages. Large-scale climatological factors [28] which seem to bear some relation to high rain rates are number of thunderstorms, late summer humidity, and total July precipitation. These are probably related because most of the rain rates large enough to cause an outage are due to thunderstorms. Terrain should also be considered since rough terrain and mountains contribute to the formation of thunderstorms. In mountainous regions, precipitation tends to increase with altitude. When moist winds are lifted by a mountain chain, the windward slope tends to have heavier precipitation than the lee side. One side of a hill exposed to prevailing winds may have very heavy rainfall while areas on the other side may be quite dry.

In addition to losses in the path, rain on antenna radomes and passive reflector surfaces can increase losses at higher frequencies. Blevis [4] derived the loss of a thin sheet of water. He then related hemispherical radome dimensions to water thickness based on rain rates. He observed that a thickness of 0.010 inch of water would be produced by 50 mm/hr of rain on a radome of 2.5-foot radius or 12.5 mm/hr on a radome of 10-foot radius. This water layer would produce 2.5-dB loss at 3.7 GHz and 8.7-dB loss at 16 GHz. Lin [21] also reported experimental results. At 12 GHz, the loss of a 10-foot diameter, 10-year old conical radome varied from 2.5 dB for a light water sprinkle to 7.0 dB for a heavy sprinkle. At 20 GHz with a 10-mm/hr water rate, a new radome caused about 2.5-dB loss while a month old radome caused 8-dB loss. Weathering of the radome caused it to hold more water than the new radome. Hogg [12] observed that during heavy rain, each antenna radome would cause 3- to 6-dB attenuation at 11 GHz and 4- to 8-dB attenuation at 20 GHz. The variation was a function of radome material, shape, age, wind velocity

Atmospheric multipath fading is relatively independent of path clearance. The fading becomes more frequent, faster, and deeper as distance or frequency is increased [10]. As frequency or distance is increased, the statistics of the received signal approach the distribution of Rayleigh. After the multipath fading has reached the Rayleigh distribution, further increase in either distance or frequency increases the number of fades to a given depth but decreases the duration so that the product is essentially constant [4].

If a received signal envelope voltage, V, at an instant of time has a Rayleigh distribution (as measured over a long period of time), the probability, p, that it has a value less than or equal to L is given by

$$p(v \leq L) = 1 - e^{-L^2}$$

v^2 = instantaneous received signal power relative to unfaded power

L^2 = specific faded power level relative to unfaded power

The instantaneous fade depth in dB is $-20 \log(v) = -10 \log(v^2)$. The specific fade depth in dB is $-20 \log(L) = -10 \log(L^2)$. For L smaller than 0.1 (fade greater than 20 dB)

$$p(v \leq L) = L^2$$

To account for the fact that fading is not as severe as Rayleigh for short, low-frequency paths, Barnett [1] modified the probability to

$$p = r L^2$$

where r is a correction factor to account for path variables. As implied by Barnett's figure 8 [1], r should be limited to the range 0.01 to 1.0 (1.0 indicating full Rayleigh fading). Lin's results [22] indicate fading is only worse than Rayleigh for paths with a relatively constant interfering reflection (such as over water paths). Fading is generally much better than Rayleigh for relatively short paths. Barnett [1] suggests r is given by

$$r = 2.50 \times 10^{-6} c f D^3$$

and direction, and rain rate. At 11 GHz, total path loss due to two wet radomes is sometimes estimated at 4 dB [21] [28] for path design purposes.

ATMOSPHERIC MULTIPATH FADING

Multipath fading generally takes one of two forms. The first, atmospheric multipath, is caused by the received signal being composed of several signals arriving at the receive site by slightly different paths from the transmitter. The different transmission paths are caused by slight time and space dependent variations in the atmospheric refractive index. This phenomenon is the same one that causes stars to twinkle at night. Since the relative time delay of the various received signals will change as the atmosphere varies randomly, the composite received signal will vary widely and rapidly. This fading will be worse if obstruction (earth bulge) or reflective fading has already reduced the level of the dominant received signal. Figure 19 shows typical received signal variation during multipath fading.

DeLange [8] noticed that for a 22-mile path operating at 4 GHz, path differences were from a fraction of 1 foot to 7 feet with 3 feet being the most common. Kaylor [14] made several observations on a typical 31-mile, 4-GHz path with no significant ground reflections. He observed that deep multipath fades (greater than 20 dB relative to normal propagation conditions) always showed definite frequency selectivity (great loss only occurred over a relatively narrow frequency range). The deep fading was caused by at least four to six different component rays.

The amplitude of the short path signals was larger than longer path signals, but depth of fade was primarily a function of long path signal amplitude. Deep fading was largely uncorrelated for frequencies separated by more than 160 MHz (4 percent separation) but was highly correlated for frequencies within 80 MHz (2 percent) of the deep fade notch. Deep fading usually occurred with a wide frequency loss of at least 10 dB (for deep fades of 30 to 40 dB, broadband losses were typically 10 to 20 dB).

Most multipath fading occurs between midnight and 9:00 am [1] during the summer and early fall [6]. Frequency diversity helps reduce deep fading but has no effect on shallow fades. The space correlation of fading signals is large in the horizontal plane. However, it is small in the vertical plane under severe fading conditions. Therefore, vertically spaced (transmit or receive) space diversity antennas can be used to reduce fading. Space diversity is as good or better than frequency diversity for multipath or reflective fading [33] and sometimes better for long, slow fades due to defocusing and ducting [35].

for f, the operating frequency in GHz, and D, the path length in miles. For D in kilometers

$$r = 6.00 \times 10^{-7}\, c\, f\, D^3$$

The c factor is a function of path location. For good paths, c is 0.25; for average paths, 1.0; and for bad paths, 4.0. some sources have expanded the range of c to 0.1 to 10. A good path would generally occur in an area characterized by dry climate, hilly or mountainous country with rough terrain, rare occurrence of calm weather or atmospheric stratification, or launch angles exceeding one-half degree. Average paths would be hilly or flat country (not marsh or salt flats) with occasional calm weather or atmospheric stratification; coastal areas with moderate to low temperatures (not Gulf Coast or over water); or hot, tropical regions with steep launch angles. Bad paths would have low launch angles over flat ground or in warm coastal regions or tropical regions, humid areas where ground mist forms, wet or swampy terrain (eg. irrigated fields), conditions favorable for atmospheric stratification (eg. broad protected river valleys, moors), or over water (eg. inland lakes, sea). Vigants [33] suggested that c could be modified to account for terrain roughness by making

$$c = 0.5\,(w/50)^{-1.3} \text{ for good paths}$$

$$c = 1.0\,(w/50)^{-1.3} \text{ for average paths}$$

$$c = 2.0\,(w/50)^{-1.3} \text{ for bad paths}$$

where w is a path roughness factor in rms averaged feet. This factor is introduced to quantify the observation that paths over rough terrain fade less than paths over smooth. Presumably this happens because stable atmospheric layering is less likely to occur over rough terrain. Figure 20 shows the calculated and observed received signal level statistics of a 30 mile path in the Dallas area.

REFLECTION (FRESNEL ZONE) FADING

The second form of multipath fading is reflective fading (sometimes called Fresnel zone fading). This fading, like that caused by atmospheric multipath, is due to the reception of several signals from several different paths. The concept is exactly the same used in optics. Indirect signals arrive due to reflections from the ground, water, nearby objects, or stable atmospheric layers. Unlike atmospheric multipath, fading due to these reflective signals is relatively slow-changing since the secondary paths are relatively stable. If the fading is due to cancellation between the main signal and a single reflected signal, the composite signal will be a minimum when the reflected signal is reflected from an obstacle an even Fresnel zone radius from the main path. The composite signal will be a maximum if the radius is odd. Generally, reflective fading is not a problem for paths over heavily wooded terrain or for paths so far above the reflecting surfaces that the transmit and receive patterns discriminate against reflections. Flat paths can have reflections. Paths over water or salt flats almost always have reflections. Reflections can be reduced by blocking the reflection (using screen or high-low path design), tilting the antenna , or using spaced antennas. It is common to use two receive antennas (space diversity) to combat the effect of multipath. Another method is to reduce antenna height at one end of the path while raising it at the other end to block the reflection or move it to a location less likely to be reflective (high-low path design). This technique makes one site elevated so as to provide the required clearance; the other site is located near ground level. The reflection point can be placed at a selected location by slight changes in the lower antenna height and geographical location. Even if the path is reflective, this technique reduces the difference between the direct and reflected paths when compared to midpath reflection.

OBSTRUCTION (DIFFRACTION) FADING

Radio waves normally travel outward along radial lines from their source, except when deviated by refraction or reflection. Another condition under which radio waves deviate from a straight line is called diffraction. Whenever radio waves encounter an obstructing object, some of the energy of the wave is diffracted at the edges of the object and becomes bent around the edge. This is a direct result of Huygens' principle of secondary radiation. This reduces the shadowing effect of objects which are opaque to radio waves. Diffraction fills part of the shadow area with some energy from the wave. The curved surface of the earth is the edge of one such object. Other objects may be buildings, trees, hills, or mountains, or structural parts of a ship or airplane. If the obstructing object is small and subtends only a small angle, as seen from the source of radiation, the region at a considerable distance behind the object may become filled in and suffer little or no shadowing effect. Close behind the object, however, shadowing will be observed. Shadowing due to the earth causes the field strength to decrease rapidly with distance beyond the radio horizon. In general, an exact determination of signal strength for various path clearances is difficult. The obstruction loss generally falls somewhere between the knife-edge diffraction and flat-sheet reflection cases shown in Fig. 14.

The first Fresnel zone radius F1 at any point on the radio path is given by the following:

F1 = first Fresnel zone radius

d1 = distance from one end of path to reflection point

d2 = distance from other end of path to reflection point

do = total length of path

= d1 + d2

f = frequency of operation

For F1 in feet, do, d1, and d2 in miles and f in GHz:

$$F1 = 72.1\,(d1\,d2 / f\,do)^{1/2}$$

For F1 in meters, do, d1, and d2 in kilometers and f in GHz:

$$F1 = 17.3\,(d1\,d2 / f\,do)^{1/2}$$

From a classical physics point of view, the quantity $(h/F1)^2$ defines the Fresnel zone (or fraction of the zone) clearance of an obstacle as measured perpendicular to the line of wave propagation. In practice it is measured in a line perpendicular to the earth. For normal microwave paths, there is no significant difference. Bullington [4] used (h/F1) to define path clearance. Since that time, common usage has been to define (h/F1) as Fresnel zone clearance rather than $(h/F1)^2$.

A particular form of diffraction loss is called obstruction fading. When the K factor becomes less than one (see Fig. 18), the radio wave is bent upward. Under extreme cases the receive path can be partially or completely blocked. This type of loss is called "Earth bulging" because the Earth appears to bulge up into the radio path. The power fades that occur due to diffraction by the earth's surface are generally supported by a subrefractive (positive) gradient of refractive index. This type of fading can persist for several hours to depths of 20 or 30 dB. The fading is essentially independent of small scale changes of frequency, but may be reduced or avoided by a proper choice of terminal antenna heights.

In mountainous terrain where terminals are located on dominating ridges or peaks, a single Fresnel zone clearance, or even less, will usually be sufficient to avoid this effect. If only a limited range of refractive index gradients is encountered, a first Fresnel zone clearance, or less, is sufficient. For those microwave paths where subrefractive index gradients are encountered, increased clearances are required. Diffraction fading in the sense used earlier may also occur when a strong super-refractive layer is positioned slightly below the terminal antennas. The severity of this type of fading will be reduced somewhat by terrain reflections or contributions from subrefractive layers positioned below the diffracting layer which can direct energy back toward the receiver. These contributions are a function of the gradients within and below the diffracting layer and also of the terrain roughness.

From experience, various rules of thumb have been developed to reduce obstruction fading to an insignificant effect. CCIR [13] suggests the following guidelines for line-of-sight radio paths (where Fl is the first Fresnel zone radius):

For frequencies below 1 GHz, allow obstruction clearance of

1.00 Fl for K = 4/3

For frequencies between 1 and 7 GHz, allow obstruction clearance of

0.30 Fl for K = 2/3

For frequencies greater than 7 GHz, allow obstruction clearance of

0.8 Fl for K = 7/10

White [41] of GTE Lenkurt proposed the following guidelines for highest reliability (heavy route) systems:

For areas of good-to-average propagation conditions, allow obstruction clearance of

0.30 Fl for K = 2/3, or
1.00 Fl for K = 4/3,
whichever is greater

K = effective earth radius factor

For h in feet and d1 and d2 in miles

h = [d1 d2] / [1.50 K]

For h in meters and d1 and d2 in kilometers

h = [d1 d2] / [12.74 K]

To adjust for ray curvature, subtract the above h value from the height of the ray above a flat earth or add the h value to the height of the earth below a straight ray.

In unusually severe propagation areas (such as southern United States coastal areas) path lengths are often limited to 20 miles to reduce the occurrence of obstruction fading to a reasonable level. Good propagation areas are regions with low humidity and/or temperatures and significant turbulence (eg, mountainous regions). Mountainous areas such as the Alps, Andes, Atlas, Himalayas, and Rockies are good examples. Average propagation areas include most of continental Europe and North America and most tropical and cold maritime countries. Difficult propagation conditions are related to high humidity and/or temperature area where atmospheric turbulence is not prevalent (layering is prevalent). In the United States, this includes the south eastern coastal region (Texas through North Carolina), Southern California, and the Great Lakes region. Most subtropical and warm maritime countries fall into this category. Very difficult propagation conditions are usually associated with high humidity and temperature and frequent, severe, extensive atmosphere layering. Tropical coastal areas and most desert regions are in this category.

POWER FADING

Power fading due to antenna decoupling refers to the loss of signal that occurs for transmission and reception of the signal outside of, or at the extremities of, the main lobe of the antenna pattern. Variation of atmospheric refraction can cause changes in the apparent angle-of-arrival of the line-of-sight ray, particularly in the vertical plane, and can therefore effectively cause a reduction in gain in the antennas used at the radio path terminals. Measurements made in the United States over a path of 28 kilometers, at frequencies of 4 and 24 GHz, show that the angle-of-arrival can change rapidly by as much as 0.75 degree above and below the normal line of sight. Another source observed 0.5 degree of angle-of-arrival variation on a 39 kilometer path. Variations in the vertical angle-of-arrival of up to one-half degree have been observed on a 40-kilometer path. This effect is proportional to the path length and can introduce several decibels of loss for high gain antennas and long line-of-sight paths. Because of the vertical variations in angle- of-arrival, antennas having half-power beam widths less than 0.5 degree should generally be avoided for line-of-sight paths. This limitation can be used as one criterion to determine maximum aperture size for antennas and the maximum vertical dimension for passive repeaters. This loss may be minimized by specifying a sufficiently broad antenna beam so that the expected variations of the angle of arrival are matched or exceeded.

DUCT FADING

Refraction (bending) of a radio wave occurs when the wave speed on one side of the beam is reduced below that on the other. The bending is in the direction of the reduced speed, and its degree is directly proportional to the amount of speed reduction with distance (ie, the gradient of wave speed) normal to the beam axis. Since refractivity N is a ratio of wave speeds, it follows that the gradient of refraction normal to the radio wave axis indicates the direction and amount of the resultant radio refraction. Refraction is a function of the gradient and not of discrete values of N. Significant gradients of N in the atmosphere normally occur only in the vertical, and these are specified as positive or negative (ie, increasing or decreasing N-values with height respectively). Positive N-gradients cause subrefraction (ie, upward bending of a radio wave), and negative N-gradients cause superrefraction (ie, bending downward toward the curvature of the earth's surface). Extreme superrefraction is called ducting or trapping, since it results in the wave following a path which approximates the curvature of the earth. Gradients of N averaged over a world wide basis are shown in Fig. 15. This figure also related N gradient to K factor. Gradients of N, which result in gradients of wave speed and refraction of a radio beam, are in turn the results of characteristics of the atmosphere. The significant atmospheric properties in this respect are water vapor content and density. Of these, water vapor content is, in general, the most important.

Whenever a horizontal layer of air has its normal properties altered so that the refractive index decreases rapidly with increase in height, strong downward bending of any nearly horizontal rays traversing the layer will occur. The curvature of these rays often exceeds the curvature of the earth's surface. A layer of air having this property is called a duct. Ducts may be divided into two types, ground (surface) and elevated. The underside of a ground based duct is in contact with the earth's surface while the underside of an elevated duct is above the earth's surface and overlies a layer of normal air. Prolonged fading, or signal enhancement, can result from propagation through ducts, especially when either the transmitter or the receiver is located within the duct. Signals may be trapped within the duct and propagated far beyond the horizon. Ducts may also cause multipath fading. Two conditions are necessary to form a duct. The first is for the refractive index gradient to be equal to or more negative than -167 N per kilometer (-23 N per mile). This means that K must be infinite (flat earth) or negative (extreme superrefractivity). The second necessary condition is that the gradient must be maintained over a height of several wavelengths. For ducts 100 to 30 feet thick, trapping will occur for frequencies between 2 and 13 GHz respectively. Of course, this cutoff relationship is only approximate since ducts have vague boundaries.

Because the energy within the duct spreads with distance in the horizontal but is constrained in the vertical direction, it is possible in principle that the field strength within a duct may be greater than the free-space field strength for the same distance. The transmission power loss might be expected to be proportional to the distance d, instead of following the free space d^2 law (power loss in dB a function of 10 log [d] rather than 20 log [d]). Some energy will steadily pass out of the top of the duct, thereby adding to the transmission loss within the duct. A consequence of this leakage is that the field strength just above a duct at a distance well beyond the normal horizon may be higher than if the duct were not present. The signal level within the duct would be higher than normal even if the transmitter were just outside the duct. Conversely, the duct may cause much lower signal strength above the duct top if the transmitter is within the duct, or much lower signal strength within the duct if the transmitter is above the duct. Normally, the refractive index gradient will not be constant with horizontal distance, so a duct will have horizontal limits beyond which the radio energy reduces rapidly. Also, the transmission loss within a duct will change considerably as a function of time as the duct characteristics change. This type of fading mechanism is the likely source of many so called space wave fadeouts. The fading is not generally sensitive to small changes of frequency or of spatial position of the antennas and cannot be remedied by commonly used diversity techniques.

Ground-based ducts may be formed by an unusually rapid decrease of water vapor with height, or an increase in temperature with height, or both effects together. Two causes associated with the sea or large areas of water are evaporation and advection. Evaporation of water vapor from the surface of the sea may cause a zone of high humidity (ie, high refractive index) below a region of drier air. Such ducts are particularly likely to occur in the afternoon due to prolonged solar heating. The duct thickness is typically 15 m. Over tropical seas, the high humidity existing near the surface produces almost permanent ducts that may contain a change of some 40 N-units. Advection, the movement of one air type over another, may cause hot dry air (from the land) to be blown over cold wet air, producing a region of low refractive index about a region of high refractive index. This is most marked at evening with the onset of a land breeze. The duct thickness is typically 25 meters. Such a duct may also form when warm dry air is blown over cold ground. Radiation cooling may also produce temperature gradients which cause ground based ducting. This occurs when the ground cools at night due to the absence of cloud cover. Air next to the ground becomes colder than that higher up, and the process continues as the ground continues cooling. The duct becomes thicker as the night continues. This phenomenon is fairly commonplace in desert and tropical climates.

There is no comprehensive data available to permit calculation of duct fading statistics for a particular path. It is generally unwise to extrapolate fading statistics for one area to apply to some other part of the world. Fading is related to local conditions and refractive index.

A severe form of fading produced by surface ducts has been termed blackout fading [17]. Low clearance paths traversing areas supporting superrefractive ground-based layers have experienced complete loss of signal for periods of up to 24 hours due to the blackout phenomenon. The fades are sudden, catastrophic, and nonselective (although widely spaced antennas are sometimes effective). A rising atmospheric layer (usually not visible, but sometimes associated with visible steam fog formed over warm water or moist ground) may intercept and trap the path. The failure is occasionally preceded by reflection fades (reflection path from the layer) and an obstruction fade.

CONCLUSION

For the last few pages the nonequipment related system design considerations have been overviewed. Radio system performance is highly dependent of the choice of proper antennas and careful path design. No single article can begin to treat the topics adequately. However, the various topics are pursued in considerable detail in [16]. The intent of this article is to acquaint the reader with the most significant system design topics.

For areas of difficult propagation conditions, in addition to the above clearance criteria, add the following

For 2-GHz paths longer than 8 km (36 miles), allow obstruction clearance of 0.60 Fl for K = 1

For all other paths, allow obstruction clearance of
0.00 Fl (grazing) for K = 1/2

For moderate reliability (light route) systems, allow obstruction clearance of

3 meters (10 feet) plus 0.60 Fl for K = 1.00

White observes that clearance evaluations should be carried out along the entire path, not just the center. Often, one criterion is controlling for obstacles near the center of the path and another is controlling near the end. Near the path ends, the Fresnel zone radius and earth bulge are negligible. However, it is good practice to maintain a minimum obstacle clearance of 15 to 20 feet. The heavy-route criteria are conservative guidelines and often result in clearance heights required only in the more difficult propagation areas. Even these criteria, however, are not adequate to protect against fading due to severe surface ducts (blackout fading). If blackout fading is expected, 150 feet of clearance above the earth at all path points for K = 1 should be imposed.

Vigants [33] of American Telephone and Telegraph (Bell System) and other Bell sources suggest the following guidelines:

For good propagation areas, allow obstruction clearance of

0.60 Fl for K = 1, or
0.00 Fl (grazing) for K = 2/3,
whichever is greater

For average propagation areas, allow obstruction clearance of

0.30 Fl for K = 2/3 or,
1.00 Fl for K = 4/3,
whichever is greater

For difficult propagation areas, allow obstruction clearance of

0.00 Fl (grazing) for K = 1/2

For very difficult propagation areas, allow obstruction clearance of

0.00 Fl (grazing) for K = 5/12

The preceding guidelines apply to the normal or main antennas. If space diversity is used, the criterion for diversity antenna clearance is less stringent.

For the diversity antenna path, allow obstruction clearance of

0.60 Fl for K = 4/3 with at least 10 feet in the first 500 feet from the antenna.

This usually permits placement of the diversity antenna at an appropriate level below the main antenna. If the path terrain is nonreflective, multipath fading improvement is achieved by placing the diversity antenna at least 200 wavelengths below (or above) the main antenna.

To analyze a microwave path for conformance to the above guidelines, the profile of the earth along the transmission path is plotted on rectangular graph paper. The microwave beam is then shown as a straight line between the two points. This represents the radio or light ray for K of infinity. An h value is then subtracted from the ray height to show beam bending due to various potential K values. The h correction value is given by the following:

h = the change in vertical distance from a horizontal reference line

p = location where h is determined

d1 = distance from p to one end of path

d2 = distance from p to other end of path

REFERENCES

[1] Barnett, W. T., "Multipath Propagation at 4, 6, and 11 GHz." *Bell System Technical Journal*, pp. 321-361, February 1972.

[2] Bickmore, R. W. and Hansen, R. C., "Antenna Power Densities in the Fresnel Region," *Proceedings of the IRE*, pp. 2119-2120, December 1959.

[3] Blevis, B. C., Dohoo, R. M., and McCormick, K. S.. "Measurements of Rainfall Attenuation at 8 and 15 GHz," *IEEE Transactions on Antennas and Propagation*, pp. 394-403, May 1967.

[4] Bullington, K.. "Radio Propagation Fundamentals," *Bell System Technical Journal*, pp. 593-626, May 1957.

[5] Bussey, H. E., "Microwave Attenuation Statistics Estimated From Rainfall and Water Vapor Statistics," *Proceedings of the IRE*, pp. 781-785, July 1950.

[6] Crane, R. K.. "Attenuation Due to Rain—A Mini-Review," *IEEE Transactions on Antennas and Propagation*, pp. 750-752, September

[7] Crane, R. K., "Prediction of Attenuation by Rain," *IEEE Transactions on Communications*, pp. 1717-1733, September

[8] DeLange, O. E., "Propagation Studies at Microwave Frequencies by Means of Very Short Pulses," *Bell System Technical Journal*, pp. 91-103, January 1952.

[9] Egli, J. J., "UHF Radio-Relay System Engineering," *Proceedings of the IRE*, pp. 11124, January 1953.

[10] Friis, H. T., "Microwave Repeater Research," *Bell System Technical Journal*, pp. 183-246, April 1948.

[11] Gunn, R. and Kinzer, G. D., "The Terminal Velocity of Fall for Water Droplets in Stagnant Air," *Journal of Meteorology*, pp. 243- 248, August 1949.

[12] Hogg, D. C.. Giger, A. J., Longton, A. C., and Muller, E. E.."The Influence of Rain on Design of ll-GHz Terrestrial Radio Relay." *Bell System Technical Journal*, pp. 1575-1580, November 1977.

[13] International Telecommunication Union (ITU), Propagation, Appendix to Section B.IV.3 of *GAS 3 Manual, Transmission Systems. Economic and Technical Aspects of the Choice of Transmission Systems*, Geneva: ITU, 1971.

[14] Jakes, W. C., Jr., "A Theoretical Study of an Antenna—Reflector Problem," *Proceedings of the IRE*, pp. 272-274, February 193.

[15] Kaylor, R. L., "A Statistical Study of Selective Fading of Super-High Frequency Radio Signals," *Bell System Technical Journal*, pp. 1187-1202, September 1953.

[16] Kizer, G. M., *Microwave Communication*, Ames: Iowa State University Press, pp. 315-440, 1990.

[17] Laine. R. U., "Blackout Fading in Line-of-Sight Microwave Links," *PIEA-PESA-PEPA Conference Presentation*, Dallas, Texas, April 1975.

[18] Laws, J. O. and Parsons, D. A., "The Relation of Raindrop-Size to Intensity," *American Geophysical Union Transactions of 1943, Part II* (April 1943), pp. 452-460, January 1944.

[19] Lin, S. H., "A Method for Calculating Rain Attenuation Distributions on Microwave Paths," *Bell System Technical Journal*, pp. 1051-1086. July-August 1975.

[20] Lin, S. H., "Dependence of Rain-Rate Distribution on Rain-Gauge Integration Time," *Bell System Technical Journal*, pp. 135-141, January 1976.

[21] Lin, S. H., "Nationwide Long-Term Rain Statistics and Empirical Calculation of ll-GHz Microwave Rain Attenuation," *Bell System Technical Journal*, pp. 1581-1604, November 1977.

[22] Lin, S H., "Statistical Behavior of a Fading Signal," *Bell System Technical Journal*, pp. 3211-3269, December 1971.

[23] Lin, S. H., Bergmann, H. J., and Pursley, M. V., "Rain Attenuation Distributions on Earth-Satellite Paths—Summary of 10-Year Experiments and Studies," *Bell System Technical Journal*, pp. 183-228, February 1980.

[24] Medhurst, R. G., "Passive Microwave Mirrors," *Electronic and Radio Engineer*, pp. 443-449, December 1959.

[25] Medhurst, R. G., "Rainfall Attenuation of Centimeter Waves: Comparison of Theory and Measurement," *IEEE Transactions on Antennas and Propagation*, pp. 550-564, July 1965.

[26] Nowland, W. L., Olsen, R. L., Shkarofsky, I. P., "Theoretical Relationship Between Rain Depolarization and Attenuation," *Electronics Letters*, pp. 676-678, October 1977.

[27] Olsen, R. L., Rogers, D. V., and Hodge. D. B., "The aR^b Relation in the Calculation of Rain Attenuation," *IEEE Transactions on Antennas and Propagation*, pp. 318-329, March 1978

[28] Osborne, T. L., "Applications of Rain Attenuation Data to 11-GHz Radio Path Engineering," *Bell System Technical Journal*, pp. 1605-1627, November 1977.

[29] Sciambi, A. F., "The Effect of the Aperture Illumination on the Circular Aperture Antenna Pattern Characteristics," *The Microwave Journal*, pp. 79-84, August 1965.

[30] Silver, S., *Microwave Antenna Theory and Design*, New York: McGraw-Hill, pp. 169-199, 413-542, 574-592, 1949.

[31] Thrower, R. D., "Curing the Fades, Part III," *Telephone Engineer and Management*, p. 82, September 1, 1977.

[32] Tillotson, L. C., "Use of Frequencies Above 10 GHz for Common Carrier Applications," *Bell System Technical Journal*, pp. 1563-1576, July-August 1969.

[33] Vigants. A., "Space-Diversity Engineering," *Bell System Technical Journal*, pp.103-142, January 1975.

[34] Wang, H.S.C., "Distortion of FM Signals Caused by Channel Phase Nonlinearity and Amplitude Fluctuations," *IEEE Transactions on Communication Technology*, pp. 440-448, August 1966

[35] White, R. F.,"Space Diversity on Line-of-Sight Microwave Systems," *IEEE Transactions on Communication Technology*, pp. 119-133, February 1968.

[36] White, R. F., *Engineering Considerations for Microwave Communications Systems*, San Carlos: GTE Lenkurt, pp. 51-52, 1975.

Table 2 Typical Radio Carrier to Interference Objectives (Cochannel Interference)

Interfered System	C/I Objective (dB) Frequency Band		
	4 GHz	6 GHz	11 GHz
1200 Channel FDM-FM	63-76	62-81	61-89
1800 Channel FDM-FM	65-85	63-83	64-94
2400 Channel FDM-FM	-	62-80	64-92
2700 Channel FDM-FM	-	63-84	73-96
5400 Channel SSB	-	54-90	-
525 Line NTSC Video	66-68	54-68	62-70
45 Mb/sec 8 PSK	65	-	75
45 Mb/sec 16 QAM	65	-	75
90 Mb/sec 8 PSK	-	65	75
90 Mb/sec 16 QAM	-	65	75
90 Mb/sec 64 QAM	72	-	-
135 Mb/sec 16 QAM	-	-	75
135 Mb/sec 64 QAM	-	72	81

Table 3 Typical Radio Carrier to Interference Objectives (Adjacent Channel Interference)

Interfered System	C/I Objective (dB) Frequency Separation				
	15 MHz	20 MHz		30 MHz	40 MHz
	6 GHz	4 GHz	11 GHz	6 GHz	11 GHz
1200 Channel FDM-FM	37-69	27-48	38-60	20-35	20-37
1800 Channel FDM-FM	57-77	35-54	49-72	20-49	20-43
2400 Channel FDM-FM	63-78	-	57-77	20-57	20-53
2700 Channel FDM-FM	-	-	58-80	-	-
5400 Channel FDM-SSB	60-90	-	-	20-51	-
525 Line NTSC Video	35-57	22-35	20-52	20	20
45 Mb/sec 8 PSK	-	25-56	20-75	-	20-45
45 Mb/sec 16 QAM	-	25	20-59	-	20
90 Mb/sec 8 PSK	60-71	-	60-75	23-66	20-34
90 Mb/sec 16 QAM	53-61	-	30-67	20-44	20-33
90 Mb/sec 64 QAM	-	32	-	-	-
135 Mb/sec 16 QAM	-	-	75	-	45
135 Mb/sec 64 QAM	67-69	-	75	20-45	20-40

Table 1 Terrestrial Frequency Planning Data

1. Site name (with user identification).
2. Latitude: degrees, minutes, seconds, north or south.
3. Longitude: degrees, minutes, seconds, east or west.
4. Site elevation (meters or feet) above mean sea level.
5. Antenna center line (meters or feet) above site elevation - include data for both main and diversity antennas if appropriate.
6. Antenna description (manufacturer, type number (eg. UHX-10), type (eg. shrouded parabolic), feed type (eg. dual polarization horn), aperture diameter (eg. 10 feet) for main and diversity antennas.
7. Antenna discrimination curves for both copolarization and orthogonal polarization (cross-polarized) signals.
8. Passive repeater size and type (eg. 10 feet by 10 feet, single billboard) and manufacturer and type number.
9. Equipment transmitter power and transmission line loss (or waveguide type and length) or transmitter power delivered to the transmit antenna.
10. Receiver transmission lines loss (or waveguide type and length).
11. Transmitter frequency in MHz to nearest kHz (eg. 5945.200 MHz).
12. Transmitter frequency stability (eg. 0.005 percent).
13. Traffic type (video, telephony, data) and specific loading. If video, specify 525-line or 625-line, NTSC, SECAM, or PAL. If FDM telephony, indicate number of channels (eg. 1800) and multiplexing plan (eg. CCITT Plan 2, 15 SGA). If data indicate bit rate and modulation method (eg. 135 Mb/s, 64 QAM) and if transmitter spectrum meets any emission mask.
14. Receiver interference susceptibility curves relating C/I to performance degradation for various cochannel and adjacent interfering signals.

Table 4 Typical Worst-case Commercial Parabolic Antenna Gain (dB Relative to Isotropic Radiator)

Diameter m (ft) Frequency (GHz)	0.6(2)	1.2(4)	1.8(6)	2.4(8)	3.0(10)	3.7(12)	4.6(15)
1.9	-	25.0	28.5	31.0	32.9	34.5	36.4
2.1	-	25.8	29.3	31.9	33.8	35.4	37.3
2.2	-	26.3	29.3	32.2	34.2	35.7	37.6
2.4	-	27.2	30.9	33.3	35.2	36.9	-
2.5	-	-	31.0	33.5	-	-	-
2.6	-	27.9	31.1	33.6	35.4	37.4	-
3.7	-	-	-	36.8	38.8	40.4	42.3
3.9	-	-	-	36.8	38.8	40.4	42.3
4.0	-	31.4	34.9	37.3	39.0	41.0	42.7
4.7	-	33.0	36.4	38.9	40.8	42.4	44.3
5.9	-	-	-	-	42.9	44.5	-
6.2	-	35.0	38.5	41.3	43.1	44.8	46.4
6.8	-	36.0	39.4	42.0	43.8	45.4	46.9
7.4	-	36.5	40.0	42.5	44.5	46.0	47.7
8.0	-	37.1	40.7	43.3	45.2	46.7	48.6
8.1	-	37.2	40.8	43.3	45.2	46.7	48.6
8.4	-	-	41.0	43.5	45.4	47.0	48.8
10.6	34.1	39.6	43.1	-	-	-	-
11.2	34.5	40.5	44.0	46.4	47.8	49.8	12.5
12.5	35.4	40.7	44.8	47.3	48.5	50.6	51.6
12.7	35.5	40.8	45.1	47.6	48.8	50.9	51.9
13.0	35.6	41.0	45.1	47.6	48.8	50.9	-
14.9	36.5	42.5	46.1	48.6	50.5	-	-
18.7	38.5	44.7	-	-	-	-	-

Table 5 Typical Copper Corrugated Elliptical Waveguide Loss

Frequency (GHz)	Waveguide Type	Loss	
		dB/100 m	dB/100 ft
1.9	EW20	2.0	0.60
2.1	EW20	1.7	0.52
2.2	EW20	1.6	0.49
2.4	EW20	1.5	0.45
2.5	EW20	1.4	0.44
2.6	EW20	1.4	0.43
3.7	EW37	3.1	0.94
3.9	EW37	2.9	0.87
4.0	EW37	2.8	0.85
4.7	EW44	4.0	1.2
5.9	EW52	4.0	1.2
6.2	EW52	3.9	1.2
6.8	EW63	4.4	1.4
7.4	EW64	4.8	1.5
8.0	EW77	5.8	1.8
8.1	EW77	5.8	1.8
8.4	EW77	5.6	1.7
10.6	EW90	10.5	3.3
11.2	EW90	10.0	3.1
12.5	EW127	11.8	3.6
12.7	EW127	11.7	3.6
13.0	EW127	11.5	3.5
14.9	EW132	15.4	4.7
18.7	EW180	19.4	5.9

Table 6 Typical Copper Circular Waveguide Loss

Frequency (GHz)	Waveguide Type	Loss	
		dB/100 m	dB/100 ft
4.0	WC-281/-269	1.2/1.3	0.36/0.41
4.7	WC-281/-269	1.0/1.1	0.32/0.35
5.9	WC-281/269	0.91/0.99	0.28/0.30
6.2	WC-281/-269/-205	0.91/0.98/1.6	0.28/0.30/0.50
6.8	WC-281/-269/-166	0.89/0.97/2.5	0.27/0.30/0.76
7.4	WC-281/-166	0.89/2.3	0.27/0.70
8.0	WC-281/-166	0.89/2.1	0.27/0.65
8.1	WC-281/-166	0.89/2.1	0.27/0.64
8.4	WC-281/-166	0.89/2.1	0.27/0.64
10.6	WC-281/-166/-109	0.91/1.9/4.5	0.28/0.57/1.4
11.2	WC-281/-166/-109	0.92/1.9/4.3	0.28/0.57/1.3
12.5	WC-281/-109	0.95/4.2	0.29/1.30

Table 7 Rain Attenuation Coefficients

F (GHz)	a	b	F (GHz)	a	b
1.0	0.0000317	0.945	11	0.0167	1.181
1.5	0.0000675	0.972	12	0.0233	1.142
2.0	0.000115	1.007	15	0.0459	1.076
2.5	0.000173	1.049	20	0.0859	1.044
3.0	0.000239	1.096	25	0.143	1.007
3.5	0.000311	1.151	30	0.228	0.955
4.0	0.000378	1.219	35	0.337	0.904
5.0	0.000515	1.377	40	0.452	0.864
6.0	0.00106	1.393	50	0.648	0.815
7.0	0.00204	1.380	60	0.775	0.794
8.0	0.00378	1.342	70	0.850	0.785
9.0	0.00674	1.285	80	0.902	0.780
10	0.0111	1.229	100	0.958	0.774

Table 8 Relative Rain Attenuation for Vertical and Horizontal Signals

f (GHz)	R (mm/hr)					
	5	12.5	25	50	100	150
11	15	16	16	16	17	18
13	11	13	15	16	18	19
18.1	12	14	16	18	19	20
19.3	11	14	16	19	21	22
30	12	12	12	12	12	12

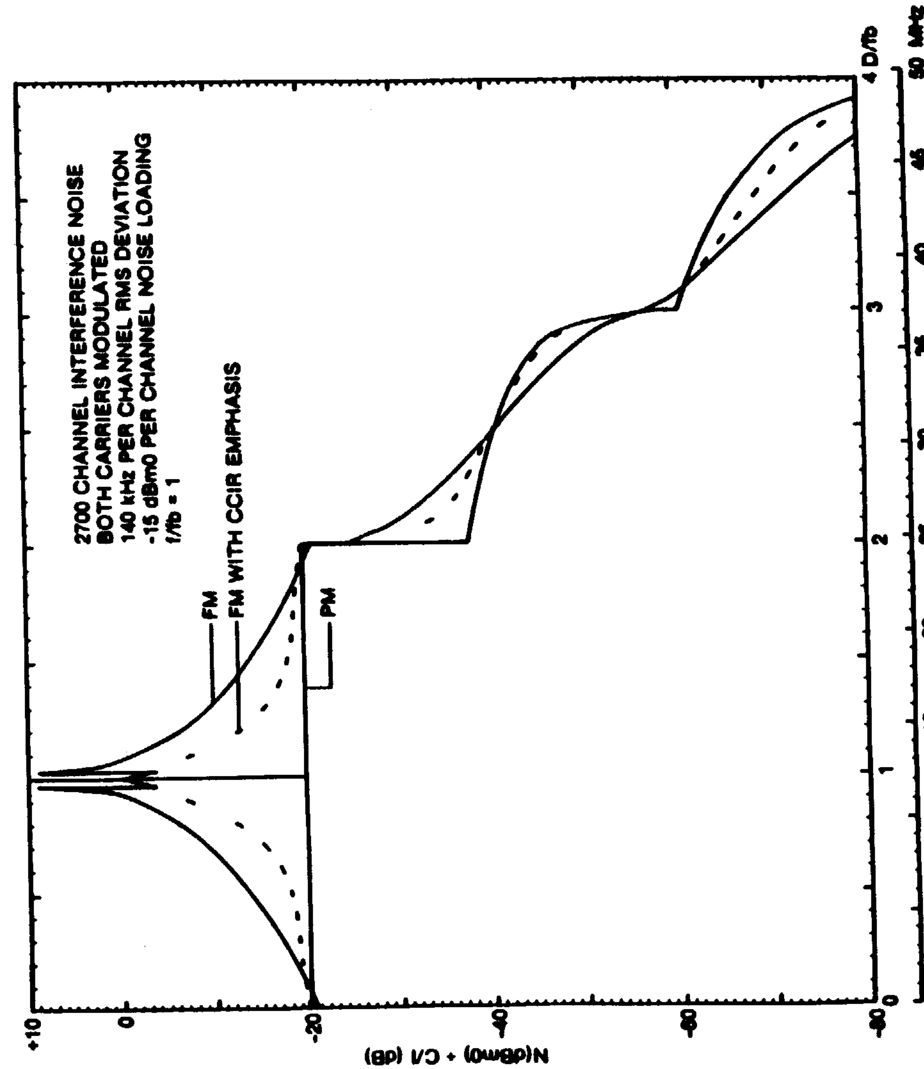

Figure 1 Analog into Analog Interference

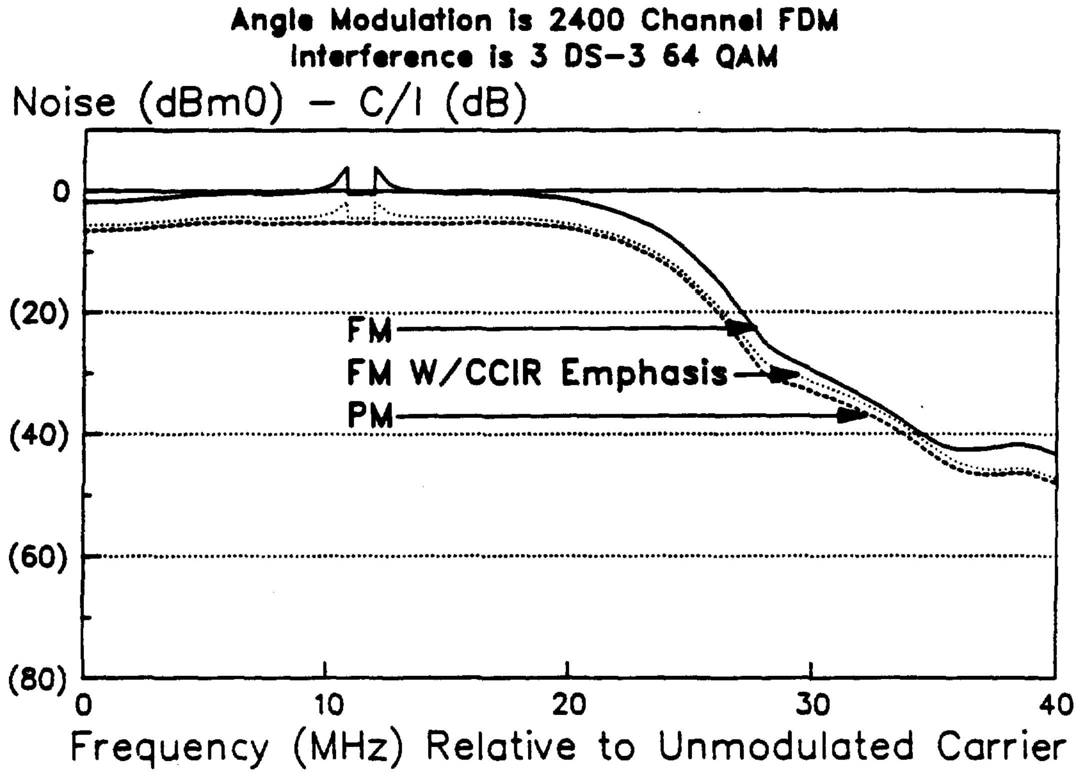

Figure 2 Digital into Analog Interference

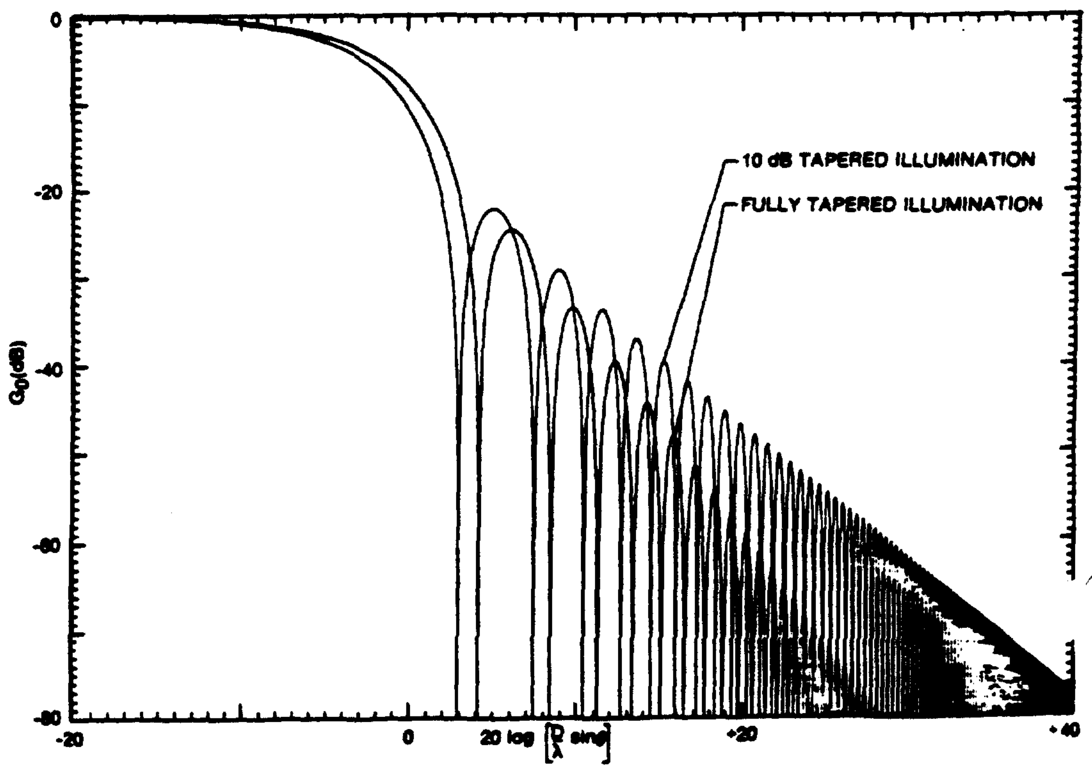

Figure 3 Circular Aperture Far Field Radiation Patterns

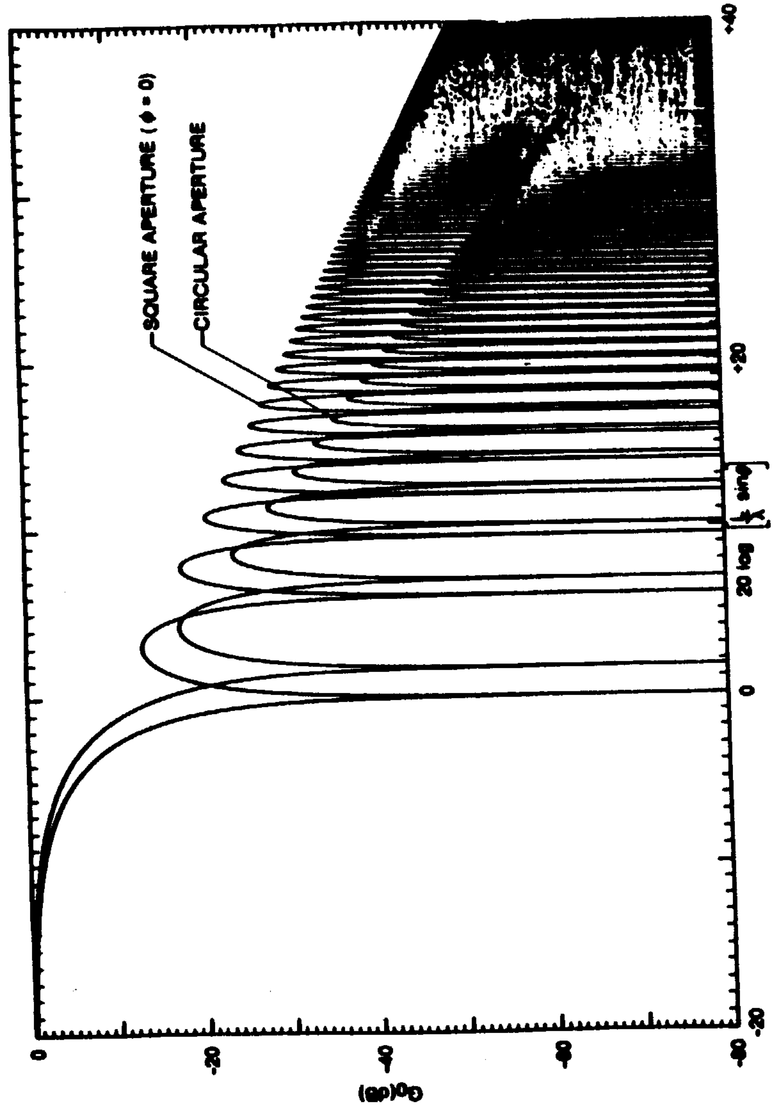

Figure 4 Uniformly Illuminated Apertures Far Field Radiation Patterns

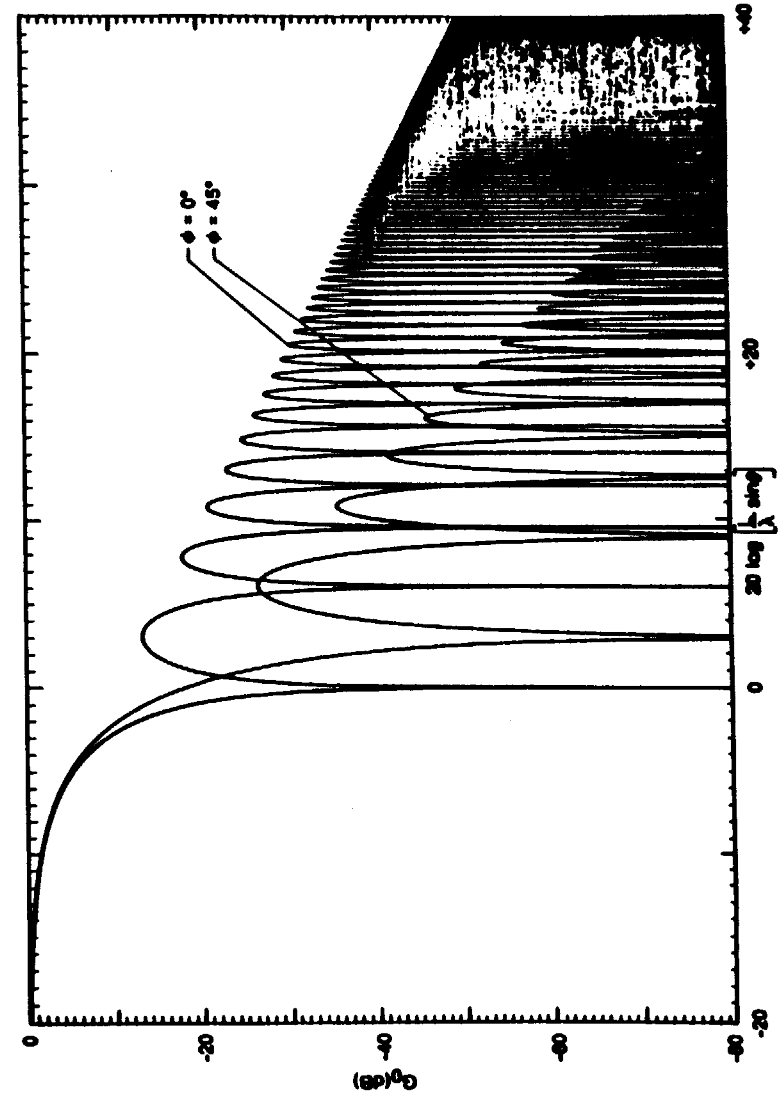

Figure 5 Uniformly Illuminated Square Aperture Far Field Radiation Patterns

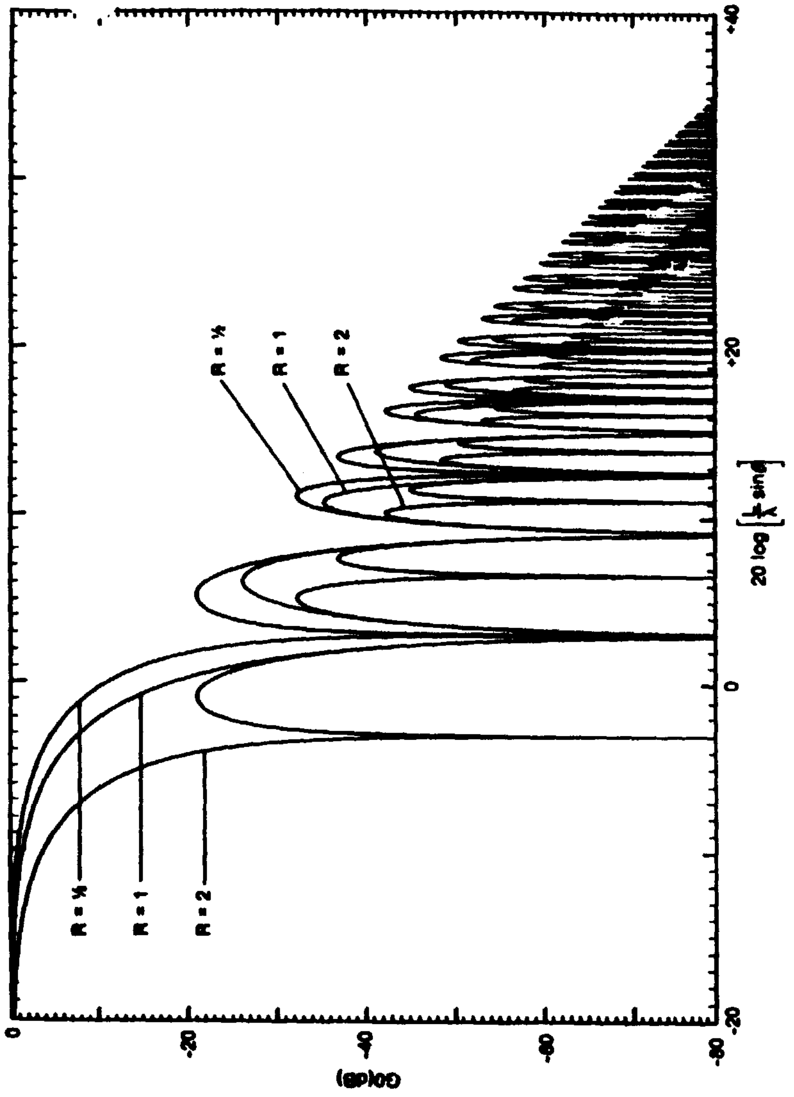

Figure 6 Uniformly Illuminated Rectangular Aperture Far Field Radiation Patterns

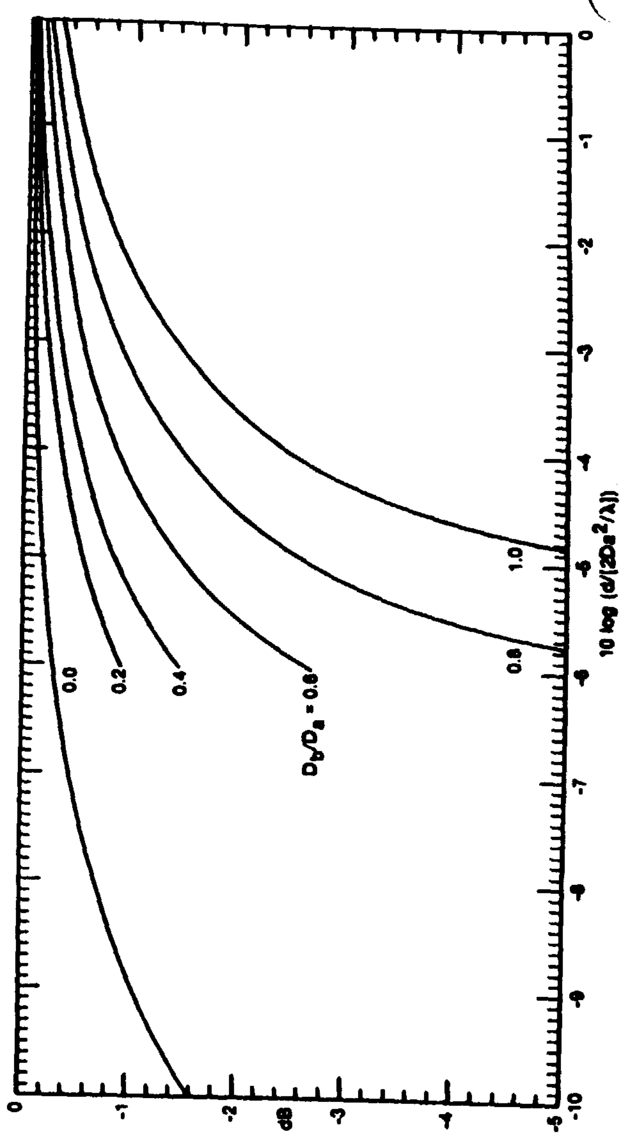

Figure 7 Dual Parabolic Antennas Near Field Correction Term

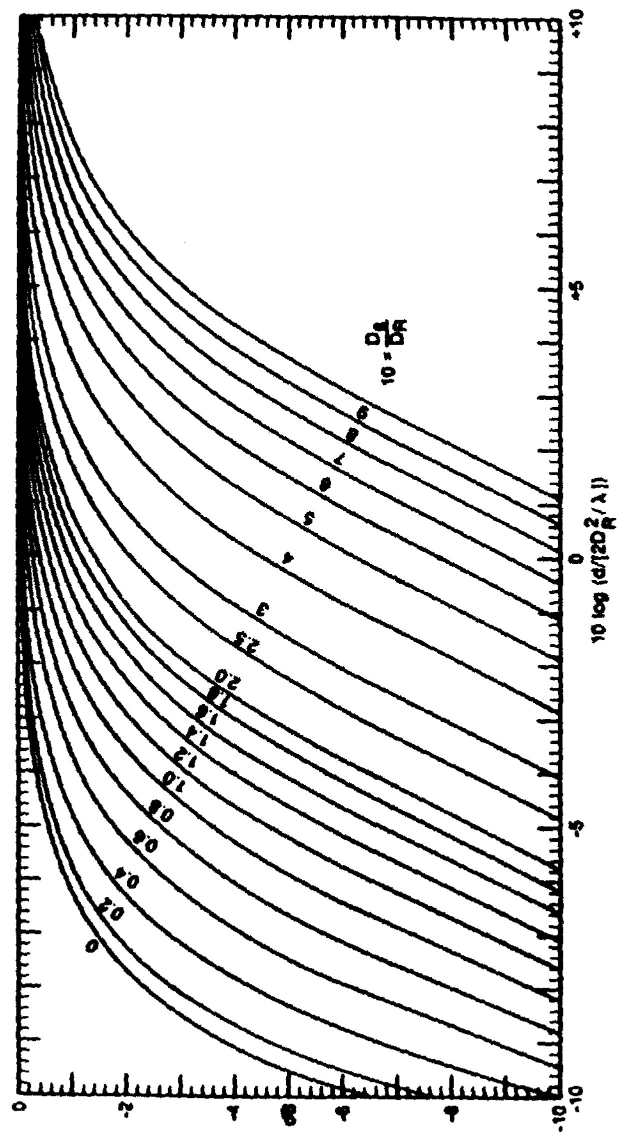

Figure 8 Circular Reflector Near Field Correction Term

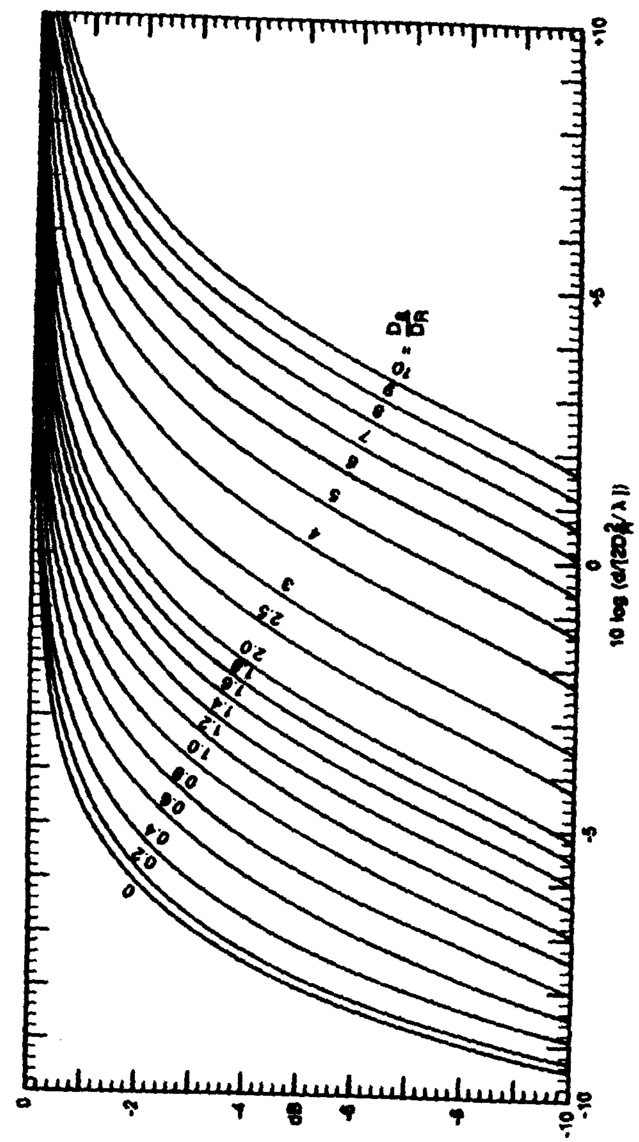

Figure 9 Square Reflector Near Field Correction Term

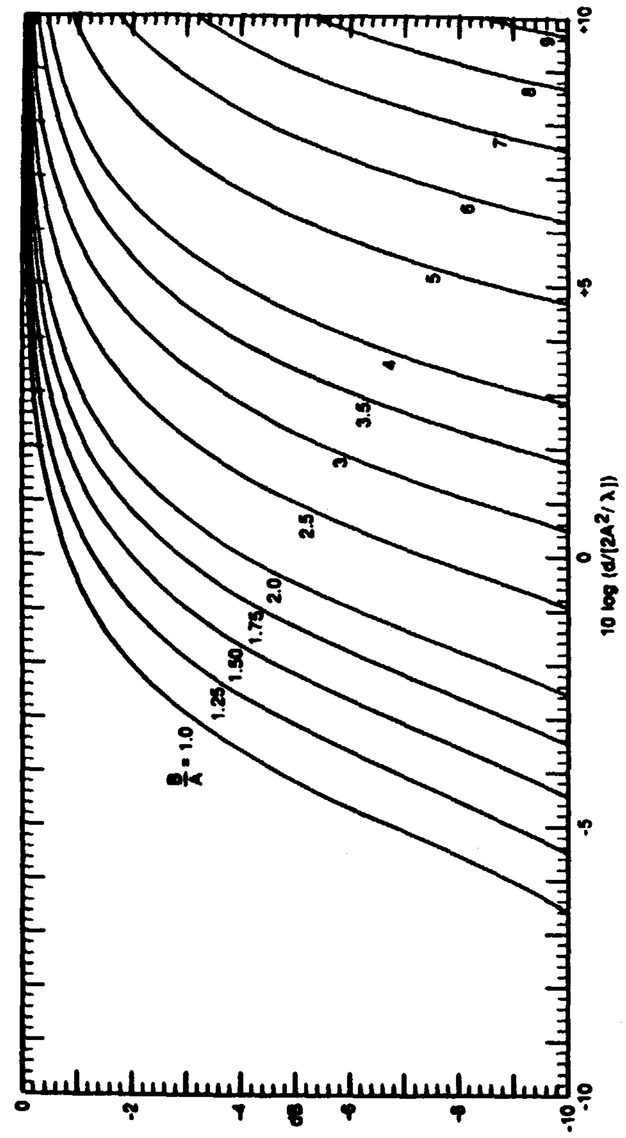

Figure 10 Dual Square Reflectors Near Field Correction Term

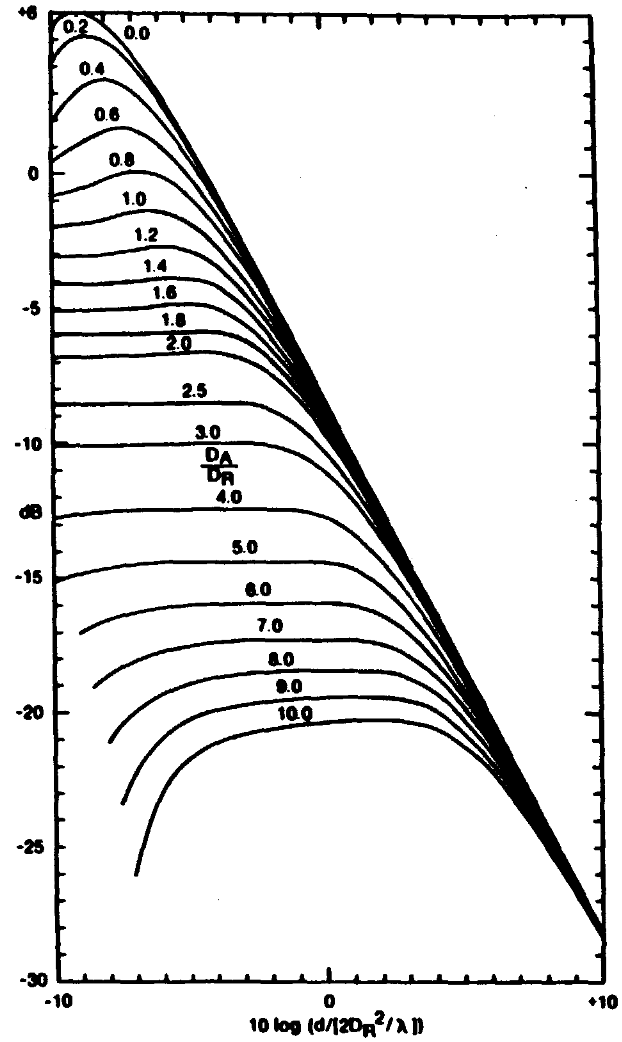

Figure 11 Circular Reflector and Parabolic Antenna Combined Gain

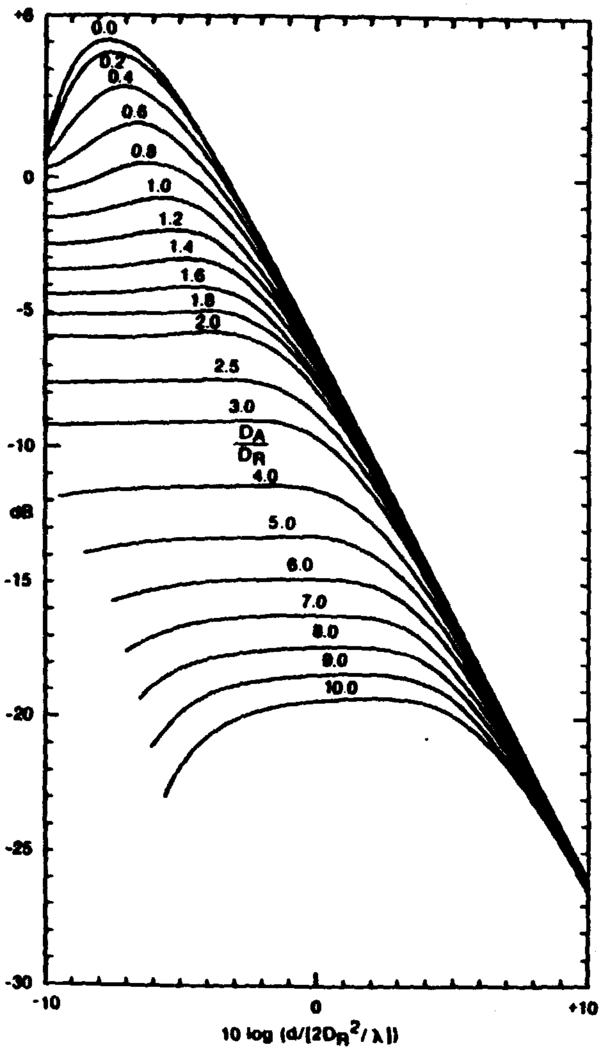

Figure 12 Square Reflector and Parabolic Antenna Combined Gain

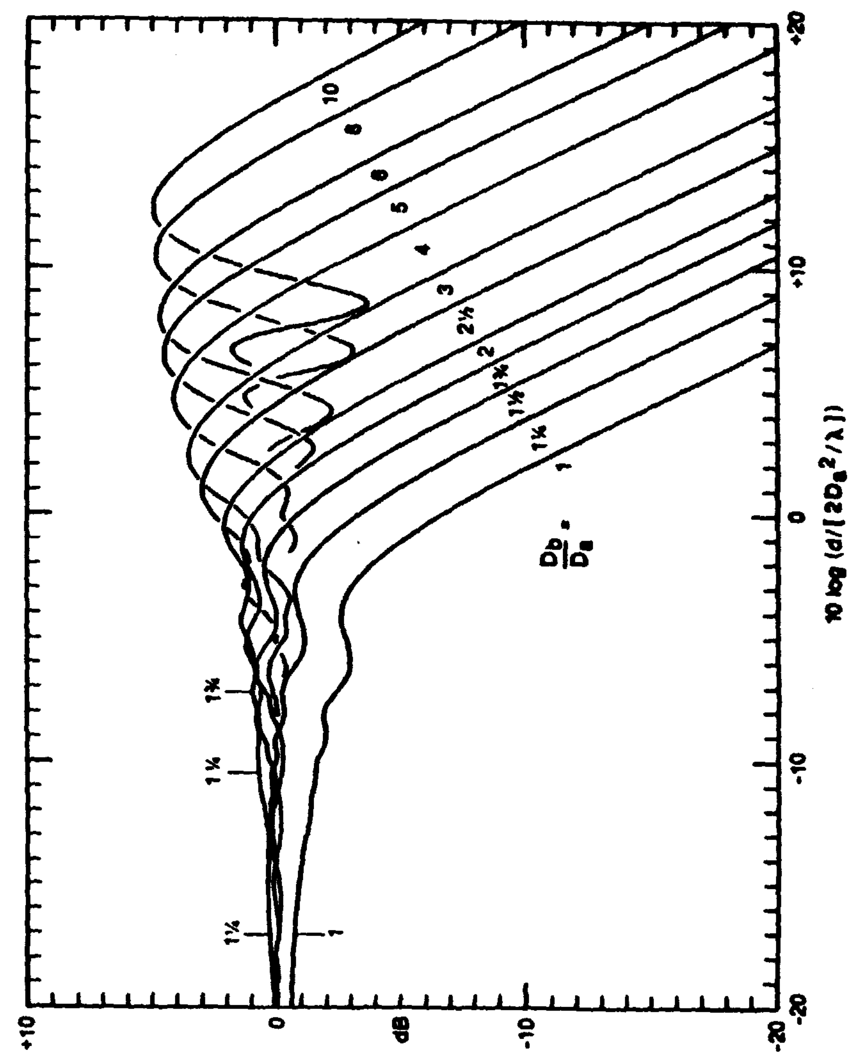

Figure 13 Dual Square Reflectors Combined Gain

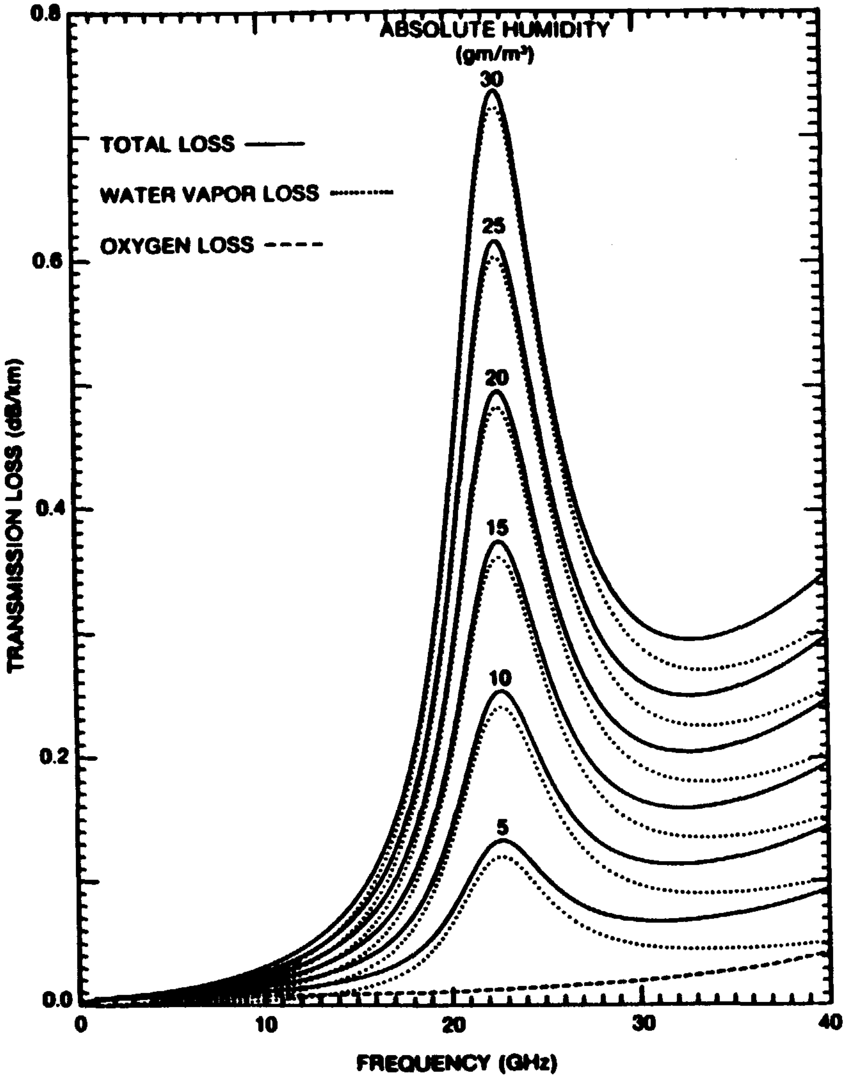

Figure 15 Nonrain Atmospheric Transmission Loss

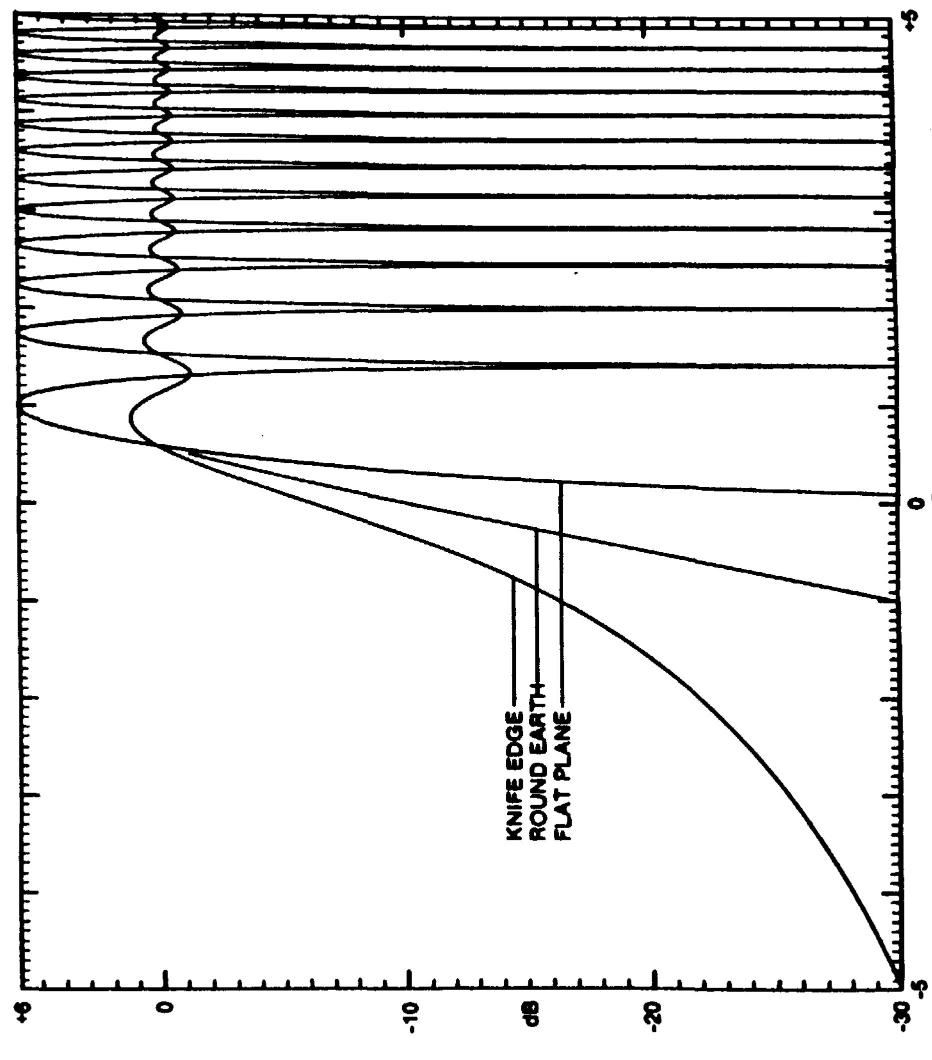

Figure 14 Obstruction Gain

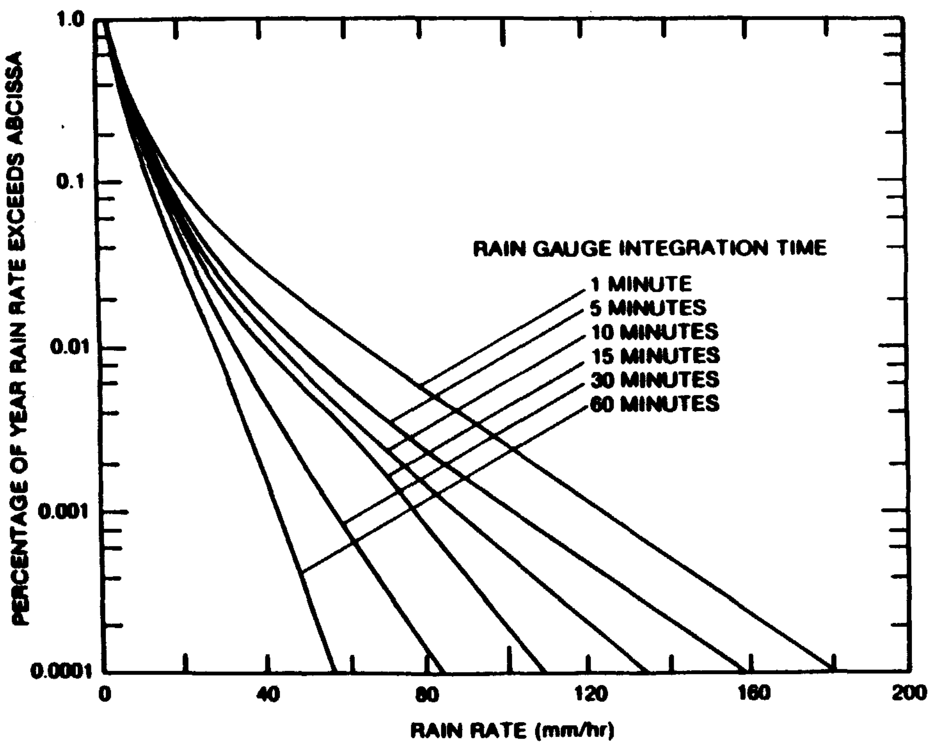

Figure 16 Averaged Rain Rates for the New York Area

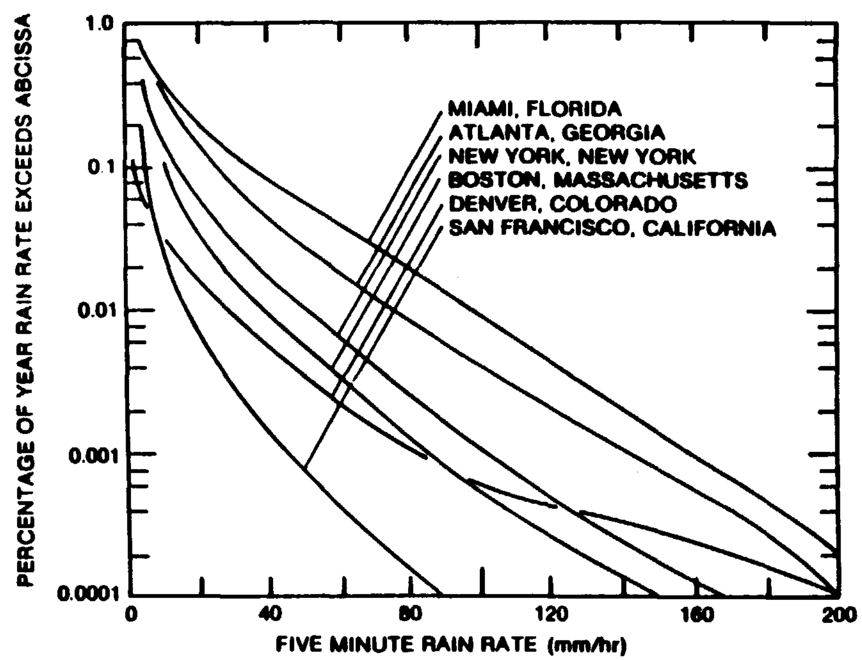

Figure 17 Long Term Rain Rates Distributions for Various Cities

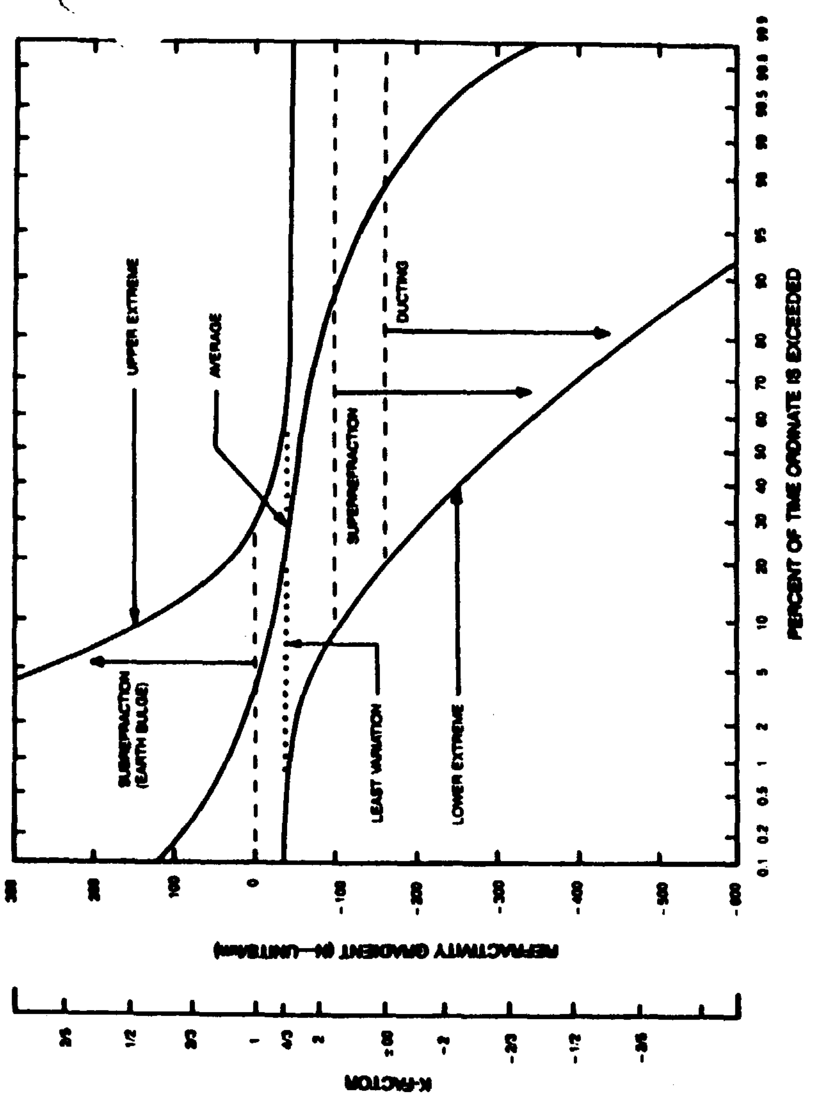

Figure 18 World Wide Refractivity Gradient (K Factor) Variation

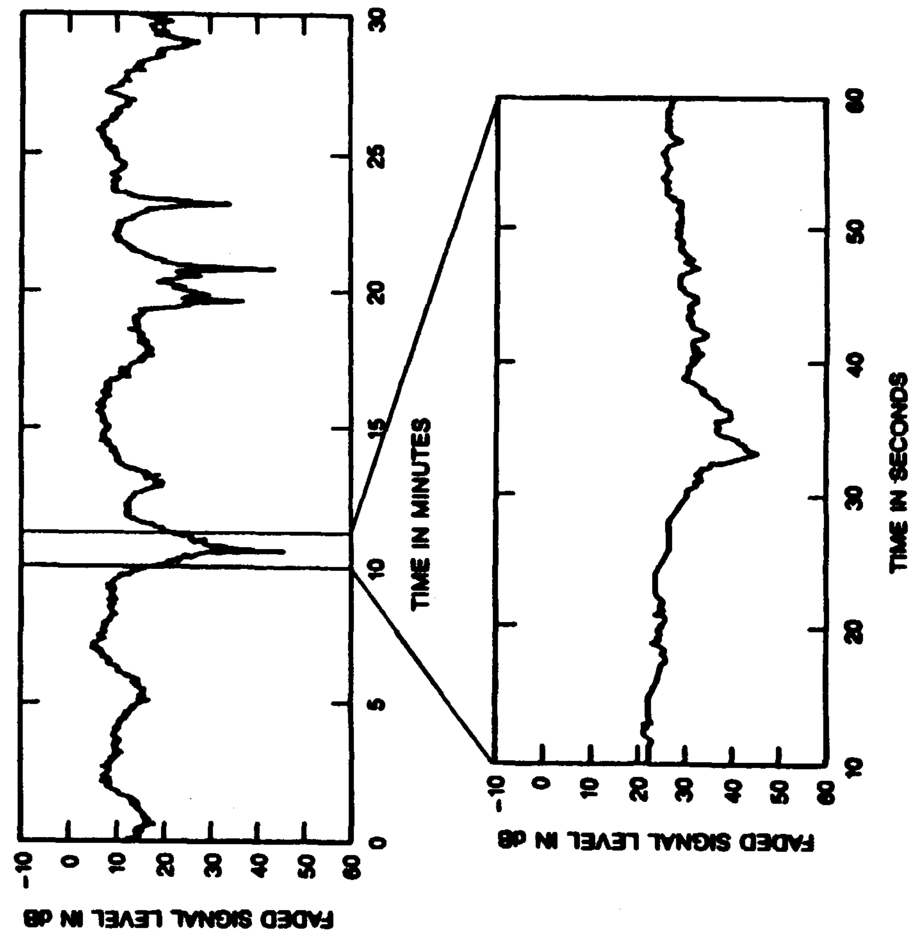

Figure 19 Typical Received Signal Variation during Fading

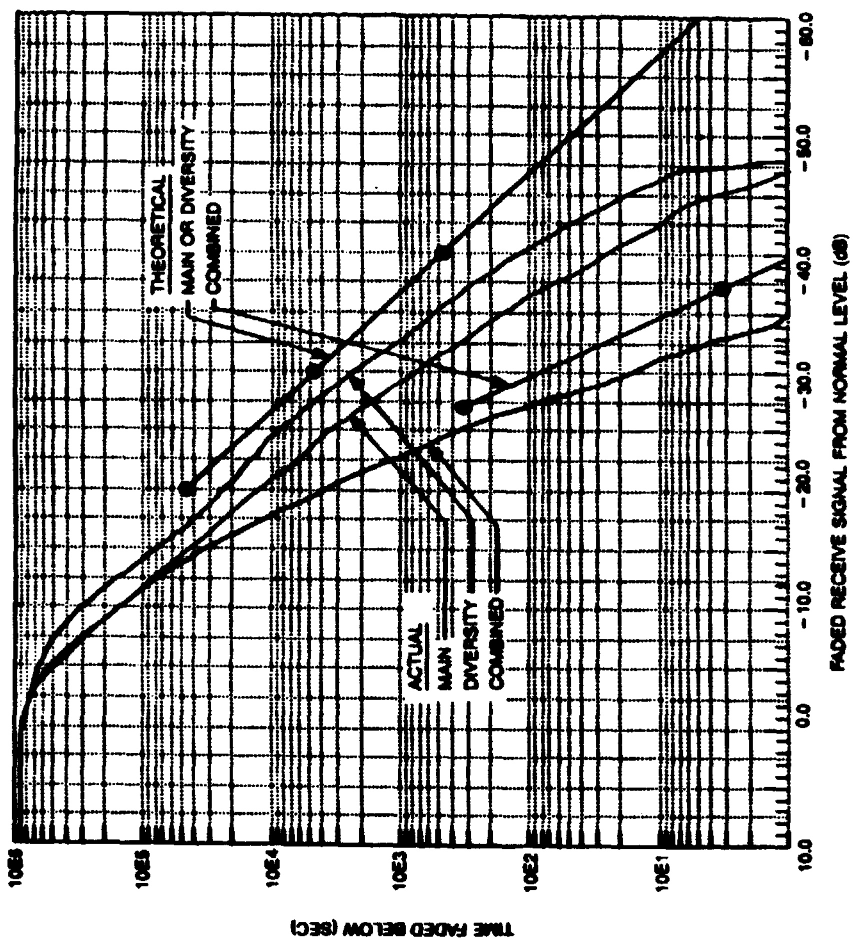

Figure 20 Year Long Received Signal Fading Statistics on Texas Path

Frequency Planning Concepts